Propulsion Hardware Selection:

Tanks and Thrusters

FAME Technical Interchange Meeting (TIM)

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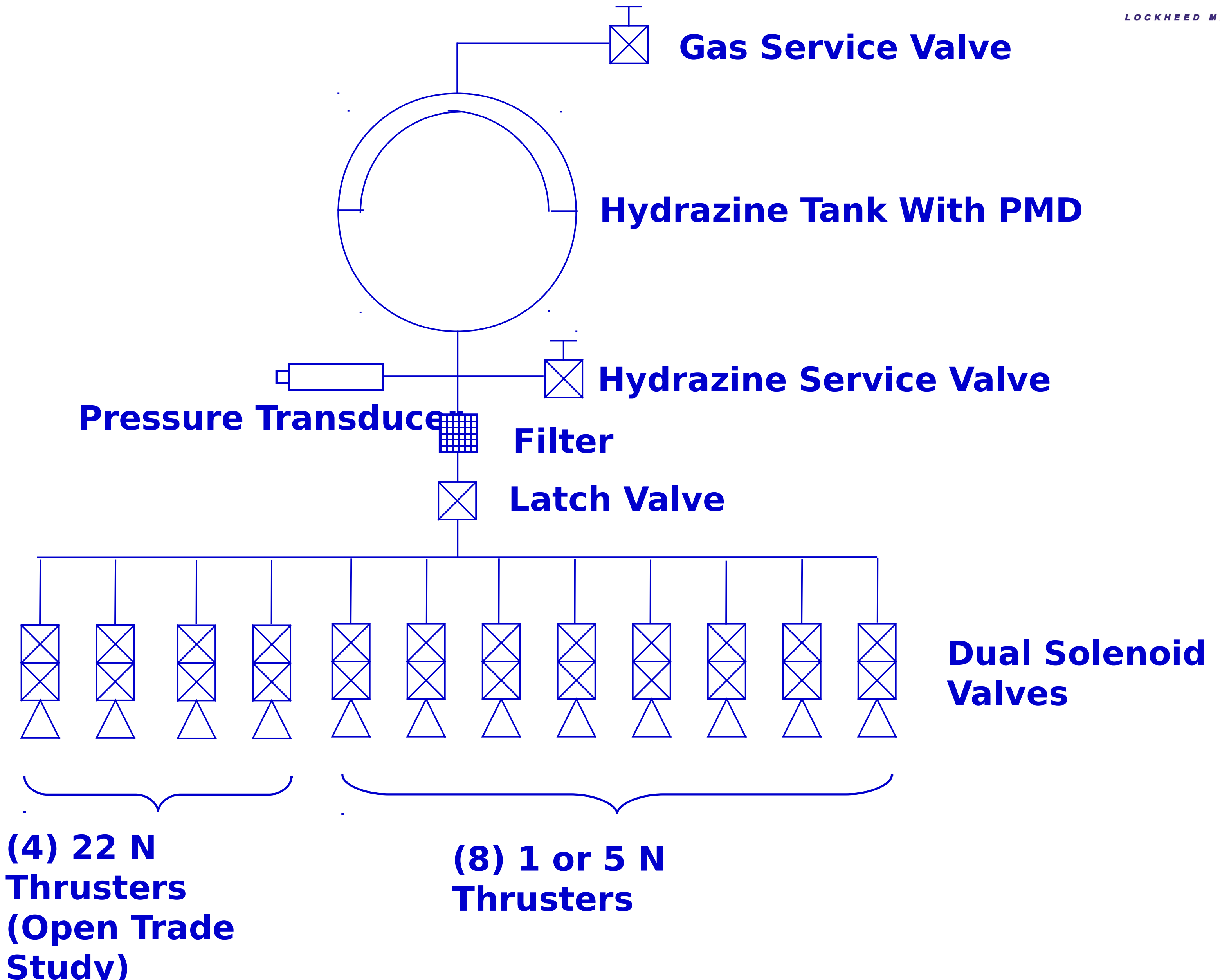
Agenda

- Propulsion System and Mission Overview
- Critical Assumptions
- Mission Analysis
- Propulsion Analysis
- Propellant Budget
- Margin Analysis
- Tank Selection
- Tank Procurement
- Thruster Selection and Procurement
- Issues

Overview: Propulsion Mission Requirements

- Provide Thrust for Spacecraft Orbit Raising, Attitude Control, and Stationkeeping
- Provide Single Fault Tolerant Design
  - Thruster Failure
  - Valve Leakage
- 5 Year Mission Life
  - Design For Delivery by August 15, 2003
    - Derived From Integrated Master Schedule
  - Design, Qualify, and Test for FAME Mission and Launch Environments
    - NCST-TP-FM001, FAME Test Plan
    - New or Re-Designed Systems Will Have Protoflight Testing
- Meet Launch Base Safety Requirements and Verification Process
  - EWR-127-1 TBD Version, Tailored for FAME
- Support Science Mission Requirements
  - Minimize CG Migration, Plume Contamination, and Minimum Impulse Bit
- Minimize Cost and Schedule Risk
  - Provide Most Flexible Design With Given Schedule and Budget

Overview: FAME Propulsion Schematic



Overview: Mission Sequence

- Launch Delta 2925 into FAME Super- Synchronous Transfer Orbit
  - 185 by GEO Alt + 320 Km
  - Apogee Selected for AKM Disposal Orbit
  - 10.6 Hour Period
  - Activate S/C and Wait 2.5 Days for Phasing and Orbit Determination
    - S/C Pointing, Slew Maneuvers, Spin- up, Spin Axis Precession, Nutation Control
- Fire On-Board STAR 37XFP Solid Rocket Motor to Circularize into a Circular Super-Synchronous Orbit
  - 1 Minute SRM Burn
  - Orbit Nominally Circular at GEO + 320 km
  - Dispose of the STAR 37XFP Transfer Stage
  - Orbit Drifts for Approximately 1 Month to Mission Longitude
    - Deploy Sunshield
    - Perform Payload Check Out
- Correct Launch Vehicle Errors and Transfer to the Mission Orbit With On-board Hydrazine System
  - 3 Axis Inertial Pointing With ACS Limit Cycle Motion

Critical Assumptions (1 of 2)

- No Major Changes to the Current Mission Design
  - Delta 2925-10 Launch Vehicle
  - Thiokol STAR 37XFP or Equivalent Solid Upper Stage
  - No Significant Changes in Mission Orbit (i.e. Inclination, Stationkeeping Requirements)
- No Major Component Failures
  - Nominal 3 Sigma Performance for the Launch Vehicle and Upper Stage
- Fuel Cg Knowledge and Propellant Slosh Are Not ADCS Control Issues for Science Collection
  - Assumption of 2 mm Cg Knowledge
- Pointing Accuracy of ±2° for Upper Stages
  - Three Sigma Error For Delta LV is Equivalent to ±1.5°

Critical Assumptions (2 of 2)

- 3rd Design Iteration Worst Case Mass Properties Dated 3/07/01 Are Representative of the Final Payload
  - Mass and Inertia Properties
- Debris Mitigation Plans Per NASA NPD 8710.3 and Assessment Per NSS 1740.14 are Approved
  - Normal Review Cycle Includes Submittals at Program PDR and CDR
- No Thruster ACS During Science Collection
  - Solar Precession, Nutation Control, or Fine Spin Control
  - Long Duration Limit Cycle Motion is Fuel Intensive

Mission Analysis Methodology

- Define Disposal Orbits for Debris Mitigation
  - Determine AKM Transfer Stage and Final FAME Disposal Orbits
    - Based on NASA Guidelines
- Evaluate Launch Vehicle Performance to FAME Insertion Orbit
  - Penalize Delta 2425 for Performance to Higher FAME GTO Orbit
    - Mass Penalty is About 10 kg
- Perform AKM Sizing
  - Performance, Loads, Propellant Requirements Including Offload, Determine Mass Allocations and Staging Efficiencies
- Perform Stage Error Analysis
  - Pointing and Total Impulse Error Evaluation and Correction
- Evaluate Orbit Design
  - Calculate Delta Velocity Requirements For Maneuvers
  - Investigate Sub-Synchronous Transfer Option
- Calculate On-Board Hydrazine Requirements
  - Size the Hydrazine Tank

Propulsion Analysis

- Solid
  - Staging Performance for the Delta and STAR 37XFP
  - System Sizing and Motor Selection
  - Calculate Propellant Offloads and Offload Capabilities
  - Perform Total Impulse and Pointing Error Analysis
- Mass Properties Investigated at the Component Level
  - Provided Solid and Liquid System Mass Input Into Mechanical Mass Properties
- Liquid Hydrazine System Fuel Sizing
  - Blowdown Pressurization Pressurization Budget
- Thruster Performance
  - Thrust, Isp, Minimum Impulse
  - Inputs Supplied to Orbit and ACS Analyst
- Final Tank Sizing
  - Hardware Selection and Availability
  - Mechanical and Geometric Constraints

ACS Analysis

- Evaluate Mission Thruster Maneuvers
  - Inertial Pointing
  - Slew Maneuvers
  - Spin Maneuvers
  - Active Nutation Control (ANC)
  - Spin Axis Precession (SAP)
  - ACS During Delta V Maneuvers
- Assumptions Throughout Analysis
  - Worst Case Mass Properties Mass and Inertia
  - Nominal Thrust Performance
  - Conservative Isp
  - Nominal Thruster Moment Arms
  - Nominal Nutation Time Constant
  - Worst Case Thruster Alignment ±1°
  - No ANC During Solid Rocket Motor Firing

Propellant Budget

Event	Event Description	Delta V (m/s)	Ave Isp (sec)	Initial Pressure (psia)	Ave Thrust (N)	Initial Mass (kg)	Delta V Prop (kg)	ACS Prop (kg)	Prop Remaining (kg)	Burn Time (sec)
0									72.6	
1	Null Delta 3rd Stage Tip Off		160	350.0	5.23	1771.1		0.13	72.4	40
2	Inertial Pointing (3-axis limit cycle)		160	348.7	5.19	1771.0		0.40	72.0	120
3	Slew Manuevers		160	345.0	5.15	1770.6		0.18	71.9	54
4	Safe Hold Mode Spin up/down		160	343.4	10.26	1770.4		0.10	71.8	16
5	Spin-up FAME with SRM		220	342.4	9.96	1770.3		2.23	69.5	482
6	Active Nutation Control		160	323.1	4.15	1768.1		15.60	53.9	5894
7	Spin Axis Precession (6 degrees)		160	231.7	3.45	1752.5		0.35	53.6	161
8	STAR 37XFP Firing		290	230.2	38030	1752.1			53.6	53
9	Active Nutation Control		160	230.2	3.34	1031.9		3.45	50.1	1618
10	Despin FAME with Spent STAR 37XFP		220	216.7	6.38	1028.5		1.95	48.2	658
11	Slew Manuevers		160	209.8	3.11	1026.5		1.00	47.2	502
12	Inertial Pointing (3-axis limit cycle)		160	206.4	3.03	1025.5		2.59	44.6	1341
13	Hydrazine to Make-up Star 48 TI Error (.5%)		220	198.1	62.63	1022.9	13.44	0.36	30.8	12
14	Hydrazine to Make-up Star 48 Pointing Alt Error		220	163.2	56.42	1009.1	0.42	0.01	30.4	0
15	Hydrazine to Make-up Star 37XFP TI Error (.5%)		220	162.3	54.87	1008.7	3.99	0.11	26.3	4
16	Hydrazine to Make-up Star 37XFP Pointing Error		220	154.2	53.46	1004.6	0.05	0.00	26.2	0.1
17	Jetison STAR 37XFP and Adaptor	0.5	220	154.1	53.36	1004.6	0.23	0.01	26.0	0.3
18	Slew Manuevers		160	153.7	2.30	890.4		0.03	25.9	22
19	Inertial Pointing (3-axis limit cycle)		160	153.6	2.30	890.3		0.24	25.7	162
20	Decrease Perigee to Final GEO Orbit	5.44	220	153.2	52.37	890.1	2.24	0.16	23.3	6
21	Decrease Apogee to Final GEO Orbit	5.44	220	148.9	50.93	887.7	2.24	0.16	20.9	7
22	Slew Manuevers		160	144.9	2.15	885.3		1.74	19.2	1271
23	Inertial Pointing (3-axis limit cycle)		160	142.1	2.10	883.6		2.15	17.0	1602
24	Safe Hold Mode spin up/down		160	138.7	4.12	881.4		1.56	15.5	595
25	Raise Apogee to Disposal Orbit	5.44	220	136.4	46.72	879.8	2.22	0.16	13.1	7
26	Raise perigee to Disposal Orbit	5.44	220	133.1	45.58	877.5	2.21	0.15	10.7	7
28	2% Unusable Residual		160	129.9	3.86	875.1	1.45		9.3	590
29	Fuel Margin		160	128.0	42.48	873.7	9.27		0.0	342

72.6 Kg (160 lb) Propellant Load

Margin Analysis (1 of 3)

- Worst Case Margin is 12.8% of Total Propellant Budgeted
  - Nominal Mission Case Margin is 24.7% of Total Propellant Budgeted
    - Nominal Mass, Thruster Performance, Error Correction
- Additional Margin is Built-in to Worst Case Margin Via Conservative Analysis Assumptions
  - Worst Case Launch Vehicle Throw Weight
  - Worst Case Mass Properties
  - Worst Case Launch Vehicle Insertion Error
  - Worst Case (Sum) STAR 37XFP Upper Stage Error
    - Can RMS, RSS, or Perform Monte Carlo Analysis
  - Worst Case Mission Plan
    - Longest Dwells at Energy Dissipating States
      - ANC, Limit Cycle Motion for Inertial Pointing
    - Highest Disposal Orbits for Debris Mitigation

Margin Analysis (2 of 3)

- **Additional Propulsion Margin is Possible**
  - **Can Fill Propellant Tank with 203 lb of Hydrazine (31% Propellant Margin) and Implement a Secondary Pressurization System**
    - **Requires 2 or 4 Pressurization Tanks to Maintain Spacecraft CG**
    - **Tank Volume of 1045 cu. In. Required for 3:1 Blowdown**
      - **Four 20.3 cm (8 in) Diameter Pressurization Tanks**
  - **Can Move to Higher Blowdown Ratio (Currently 4.78:1)**
    - **Higher Beginning of Life Thrust and Lower End of Life Thrust**
    - **Re-Evaluate Tank Maximum Pressure of 350 psia**
      - **Current Safety Margin is 2:1, Can Move to 1.5:1**
- **Additional Delta V Margin**
  - **Above GEO Disposal Orbit is CSR Baseline but Below GEO Disposal Has Staging Efficiency That Reduces Overall System Mass**
    - **Increases Effective Launch Vehicle Throw Weight**
  - **Conservative Isp of 220 vs. 230 sec**
- **Additional AKM Propellant Option**
  - **Overfill the AKM to Guarantee No Orbit Undershoot with Solid**
    - **Solid Has Higher Isp Performance and Extra Propellant Capability**

Margin Analysis (3 of 3)

- Orbit Analysis Performed for LV and Transfer Stage Errors
  - Worst Case Delta V's Generated (Poor Man's Monte Carlos)
    - Lowest LV GTO Orbit, Lowest STAR 37XFP Performance
  - Error Correction Would Occur at More Efficient Orbital Positions
    - Apogee Error Corrected in GTO
    - Delta V Equivalent of 39.1 m/s (Propellant Budget Carries 49 m/s)
- Additional ACS Margin
  - Increase Thruster Moment Arms with Booms
  - Reduce 1 Hour Pre AKM Spin Time (Nutation Control Propellant)
  - Lower Intermediate Spin Rate Prior to High Spin at AKM Firing
  - Eliminate or Relax Inertial Pointing Requirements for Limit Cycle Motion Allowing a Possible Flat Spin Attitude
    - Requires Power and ACS Sensor Analysis
  - Can Boost Conservative Isp of 160 to 180 sec for Thruster Pulse Mode Operations
  - Implement Pure Off-Pulse ACS for Delta V Maneuvers

Tank Selection (1 of 2)

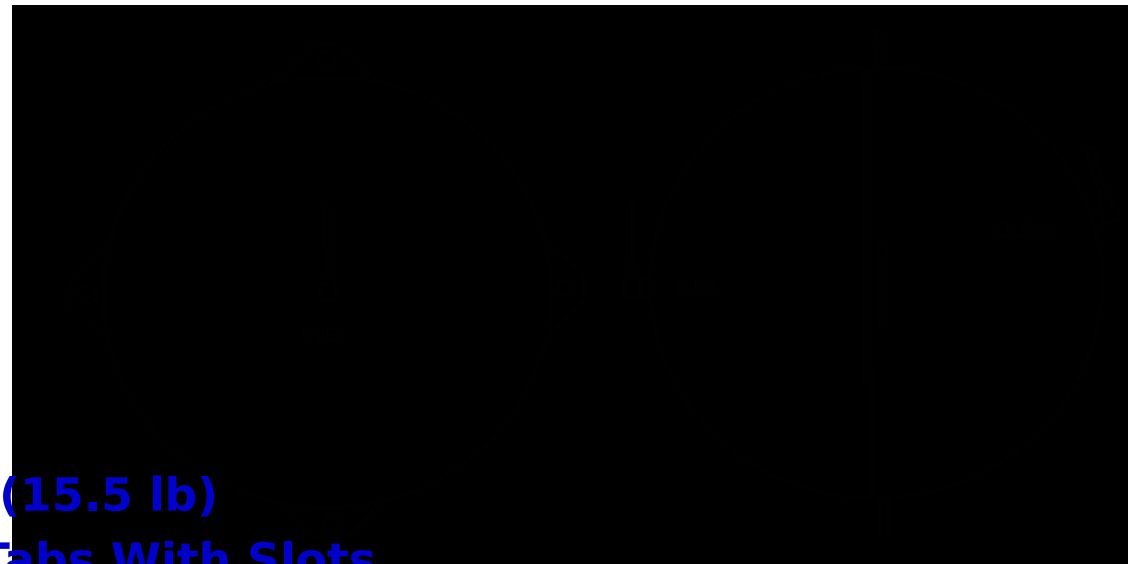
- Tank Selection Issues Requires Additional Analysis
  - Requires Quantification of Propellant and Pressurization
  - Single Blowdown Tank vs. Augmented Pressurization Tank
- Tank Geometry
  - Oblate Spheroid Desired but Has Limited Availability
    - Reduces Spacecraft Overall Height Allowing Preferred Sun Angle Between the Sun Shield and Payload
  - Mounting Options Include Boss and Girth (Tabs or Skirt)
- PMD Selection Limits Availability
  - Passive PMD Is Not Possible (Accelerations, Spin, and CG Control)
  - Trade Elastomeric Tank Bladder vs. Metal Diaphragm
    - Metal Diaphragm Has Higher ΔP From Gas to Liquid
    - Metal Diaphragm Has Better Cg Control During Accelerations
    - Metal Diaphragm Is Single Use Only
    - Metal Diaphragm Eliminates Gross Mass Motion Slosh
    - Elastomeric Diaphragm is Less Expensive

Tank Selection (1 of 2)

- Cost and Delivery Schedule
  - Heritage Design Is Desirable
  - New Design and Qualification Possible (Lengthy Delivery and Costly)
  - New Tank Design and Qualification Requires 24 Months ARO
    - Program Schedule Supports New Tank Procurement
    - Multiple Designs and Vendors Available
      - PSI, Atlantic Research, Arde, Keystone
- Implication of Oversizing the Hydrazine Tank
  - Lowers the System Blowdown Ratio
    - Smaller BOL to EOL Thrust Variation
      - Effects on Nutation Control (Requires High Thrust)
      - Effects on Minimum Impulse (Requires Low Thrust)
    - Can Overfill to Correct Blowdown Ratio
      - Mass Penalty for Unused Propellant
  - An Oversized Tank is an Excellent Reservoir for Mass Margin
    - Allows for Contingency Operations, Science Mission ACS, or Extended Mission

Tank Baseline: PSI P/N 80388

- Maximum Expected Operating Pressure (MEOP) 350 psia
- Proof Pressure 527 psia, Minimum Burst 700 psia
- Qualified Propellant Load of 72.56 kg (160 lb)
- Geometry
  - 57.15 cm (22.5 in) Outside Diameter
  - Spherical with Offset Polar Outlet Tube
  - Volume 91.1 Liters (5555 cu in)
  - Tank Weight 7.03 kg (15.5 lb)
  - Four Girth Mounted Tabs With Slots
  - AF-E-332 Elastomeric Bladder



- Designed and Previously Flown for KoreaSat, CENTAUR, TOMS-EP, ROCSAT, KOMPSAT, INMARSAT 3, GGS
- Full Mil-Std-1522 Design, Analysis, and Qualification Testing
  - One Known Safety Waiver Required for Last Girth Weld Stress Relief

Tank Procurement Status

- Component Specification Under Development
  - Document Number TBD
- Detailed Discussion With Potential Vendors Ongoing
  - PSI, Arde, Atlantic Research, Keystone
- Baseline PSI Tank is Off-the-Shelf With 18 Month Delivery
- Procurement Package Compiled and Submitted by 13 April 01
  - Initiated Dialog with Contracts Personnel
    - Purchasing Agent TBD
- Auxiliary Pressurization Tanks Are Still Under Investigation
  - Lead Time is Shorter Since Tank Does Not Have PMD
    - 14 Month Delivery Allows a PDR Decision
  - Multiple Vendors Possible
    - Kaiser Compositek
    - Lincoln Composites
    - Structural Composites Industries (SCI)

Propellant Slosh

- Fuel Sloshing in the Propellant Tank Has Not Been Analyzed
- Gross Mass Sloshing is Well Understood
  - CG Control During Expulsion and Accelerations
    - Controlled With Tank Specifications
    - Verified With Qualification or Acceptance Testing
      - Non-Destructive Testing is Possible With Elastomeric Diaphragm Tank but Not Metallic Diaphragm
- Fine Motion of Propellant and Damping Characteristic is Not Well Understood
  - Interaction Between Excitation Sources and Damping Propellant Motion
    - Evaluate All Excitation Sources: Thrusters, Motors, Torque Rods, Thermal Variations, Eclipse Effects
    - Model Propellant Viscous Motion and Damping Effects
  - Mathematical Models Will Take Several Months to Generate
  - Model Verification Through Testing is Not Possible
  - 1g Environment Swamps Subtle Slosh Effects

Thruster Procurements

- Component Specification Under Development
  - Document Number TBD
- Detailed Discussion With Potential Vendors Ongoing
  - General Dynamics, Atlantic Research, ValveTech Consortium
- Procurement Package Compiled and Submitted by 13 April 01
  - Initiated Dialog with Contracts Personnel
    - Thrusters Delivery Is 20 Months
    - Purchasing Agent TBD
- Minimum Impulse Bit Under Investigation
- Multiple Vendors Available
- Multiple Thruster Procurements On-Going For Other Customers
  - Manufacturing and Cost Efficiency

Hydrazine Thrusters (1 of 2)

- Thruster Quantity and Force Selection
  - 8 1N or 5N (from CSR) Thrusters
    - Spin Control and 3-Axis ACS
  - Zero, Two, or Four 22 N Thrusters
    - SAP, ANC, and Vehicle Delta V Thrusters
  - Minimum Impulse Bit and Maximum Thrust Are Design Drivers
    - Conflicting Requirements for a Single Thruster Size
- Multiple Designs and Vendors Including
- Hamilton Standard 22N (5 lbf)
  - In Stock at NRL From Previous Programs
  - Single Seat Valve Originally Included was Replaced with Dual Seat Valve For Clementine
  - Documentation Status Unknown
- Atlantic Research 22 N Thruster
- MR-106E 22 N (5.0 lbf)
- MR-50S,T 22 N (5.0 lbf) GOES, Viking, GPS, Voyager
- MR-111C 4N (1.0 lbf) Flown on Clementine

Hydrazine Thrusters (2 of 2)

- MR-111E 2N (0.5 lbf)
  - Possible Compromise Between the Conflicting Small Impulse and High Thrust Requirements
- MR-103C 1N (0.2 lbf)
  - Small Impulse Bit, but Being Discontinued by Manufacturer
  - Ibitmin= .0044 N-sec @15ms and 100 psia
- MR-103D 1N (0.2lbf) Long Life Thruster Variant
  - More Costly Than Warranted by FAME Mission Requirements
- MR-103G 1N (0.2 lbf) IRIDIUM Design
  - Ibitmin= .0133 N-sec @15ms and 100 psia
- MR-103H 1N (0.2 lbf) Smallest Impulse Bit
  - Single Fast Acting Solenoid Valve Rather Than Dual Valves
  - High Cost ~$80K
  - Ibitmin= .0022 N-sec @15ms and 100 psia
- ValveTech Consortium 0.2 lbf Low Cost Thruster
  - Recently Flight Demonstrated
  - Qualification and Delivery Status TBD

Propulsion Issues

- Validity of Critical Assumption Used to Select Tank
- Tight Schedule to Meet Government Procurement Deadlines
  - Expedited Procurement Process Required If Procurement is Delayed
- Undefined Tank Slosh Requirements
- Major Procurements Are Well Before CDR (Sept 01)
  - Analysis Accuracy Due to Vehicle and Mission Design Uncertainty
- Minimize Different Thruster Designs for Cost Efficiency (Specifications, Procurements, Integration, and Test Simplification)
- Thruster Solar Precession Back-Up Requirement
  - Small Impulse Bit Control System Would Be Required
  - Requirement Evaluation and Definition Are Necessary
    - Long Lead Items Are Required
    - 18 Months for the Tank
      - TBD Months for Pulsed Plasma Thruster
- Thruster and Tank Analysis Are Still Under Investigation
  - We Have the 90% Answer - Good Enough